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FAR INFRARED ALL-SKY SURVEY

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Introduction

This grant supported research in infrared technology development and balloon observations at the University of California at Berkeley from 2-1-76 through 4-30-90. All technical and scientific achievements under this grant were published in a timely fashion and are available in the open scientific literature. Consequently, this final technical report will summarize the nature of the work done under this grant, the results achieved, and the location and contents of the relevant publications.

History of Supported Research

At the time of the 1975 Snowmass Space Science Board Study on Infrared and Submillimeter Astronomy, the need for an All Sky Survey at submillimeter wavelengths was recognized. It was believed that such a survey could be carried out from a balloon platform with reasonable extensions of existing technology. Work on such a survey began under this grant in 1976. The level of funding was only sufficient to support one graduate student, so time scales for the development were quite long.

A one-meter F/1 Cassegrainian telescope was built with low emissivity diamond-turned copper reflecting surfaces. A 7-wavelength high throughput bolometric photometer was built which used "cold hole" optics of the type required to obtain low backgrounds on ambient temperature telescopes. The technology of composite submillimeter bolometric detectors was improved substantially. These improvements included the first absolute measurements of the optical efficiency of high throughput submillimeter bolometers, the first use of neutron-transmutation doped thermometric material with ion-implanted contacts, explorations of non-thermal nonlinearities and other pathologies now known to be associated with such detectors, the development of low-noise amplifiers with small 1/f noise, and the development of submillimeter-wavelength filters with sufficient out-of-band rejection at short wavelengths for astronomical observations. A balloon gondola was constructed to fly the telescope and photometer. Telemetry electronics, star sensors, magnetometer systems, and calibration systems were developed and constructed.

The engineering flight of this new gondola took place on 4/79, which revealed several system weaknesses. These included the difficulty of pre-flight testing the responsivity of bolometers which are overloaded by 300 K background radiation, and the appearance of an unidentified interference signal. The first attempt at a science flight of the all-sky survey took place in 8/82. All systems worked well, but the data were badly contaminated by interference during the flight whose source could not be identified by the available diagnostics. This interference can now be recognized as electromagnetic in origin, coming primarily from radar surveillance. High-sensitivity bolometric receivers with the optical design optimized for multi-channel, ambient-temperature, high-throughput telescopes are now recognized to be especially sensitive to such interference.

In hindsight, it is clear that the assessment of the technology for a submillimeter all-sky balloon survey in the Snowmass report was overly optimistic. The primary benefits of this program through 1982 were a large number of improvements in bolometric receiver technology, which have contributed markedly to the success of later balloon, rocket, and space projects. The knowledge developed of what would work, and what would not work contributed not only to COBE but also to the current planning for SIRTF and the Submillimeter Moderate Mission. Perhaps the most dramatic development of this kind was the introduction of the concept of an adiabatic demagnetization refrigerator to cool bolometers to 100 mK. The first prototype for an astronomical ADR was built, which has led directly to implementation of this technology for AXAF and SIRTF.

Research under the All-Sky Survey grant was reorganized in 1980 to fund continued balloon measurements of the spectrum of the cosmic microwave background. The group doing the All-Sky Survey project had been previously very successful in measuring the spectrum of the CMB from a balloon. This first experiment showed that the spectrum has a peak and falls on the high-frequency side as expected for a blackbody with a temperature of approximately 3 K. The data obtained, however, did not fit the blackbody curve perfectly. This led to widespread speculation (more than 50 publications) about distortions in the spectrum of the CMB.

A new CMB spectrum balloon experiment was designed specifically to search for systematic errors in the earlier measurements. This new experiment was first flown in 11/83 and later in 4/87. The results conclusively showed that the earlier measurement contained an ~10% contribution of radiation from the warm top of the antenna. The corrected data contained no evidence of any distortion of the cosmic microwave background. At the same time, the experiment placed useful limits on the large-scale anisotropy of the microwave background at near-millimeter wavelengths.

After several years of exclusive focus on measurements of the spectrum of the CMB, it was decided in 1986 to return to the goals of the far-infrared all sky survey using high-throughput bolometric detectors from a 1-m balloon telescope. It was determined that the most outstanding scientific project for such an approach was measurements of the anisotropy of the cosmic microwave background on angular scales from 0.3 to 3°. Based on the large-bodied experience obtained with the original all-sky survey telescope, a number of radically different approaches were implemented. The telescope was changed to a very low background off-axis design with a nutating secondary mirror for sky modulation on angular scales of 1°. The photometer was changed to a dichroic design with a flared Winston cone feedhorn. A radically different approach was used for high-throughput filters. The composite bolometers used neutron transmutation doped thermometers and operated at 0.3 K using ^{3}LHe as the refrigerant. The development of an adiabatic demagnetization refrigerator and 100 mK bolometers was begun.

A highly successful first flight of this apparatus took place in 11/89 yielding useful limits on the anisotropy of the microwave background, as well as substantial data on the galactic plane at near-millimeter wavelengths. This project is being continued under a new grant number and at the time of writing this report it has flown again with improved detectors.

Perhaps the most important feature of the new all-sky survey program is the preparations being made to fly an adiabatic demagnetization refrigerator which is a prototype for the refrigerator to be used on SIRTF. The preparation of this refrigerator for balloon observations has made a number of critical contributions to the SIRTF program. It has permitted graduate students and postdocs to work on SIRTF hardware with some prospect of science results on a short enough time scale for career advancement. The balloon project has pioneered a number of technical developments including a mechanical heat switch, an analog refrigerator controller, and radio-frequency shielding, all of which will be incorporated into SIRTF. This balloon-flight testing of SIRTF hardware has been so successful that it should serve as a model for future attempts to prepare novel technology for space.

Publications

A large number of papers were published during the tenure of this grant in order to release the scientific and technical results to the community in an orderly fashion. The research reported in most of these papers was directly funded by the grant. In a few cases, papers are included where the research was directly stimulated by the needs of grant research, but was funded all or in part from other sources. The contents of each publication are summarized by symbols as follows: detector development (D), scientific results on the spectrum of background radiation (S), development of filters (F), development of optical systems (O), and scientific results on the anisotropy of background (A).

1. N. S. Nishioka, P. L. Richards, and D. P. Woody, Composite Bolometers for Submillimeter Wavelengths, Appl. Opt. 17, 1562 (1978). (D)

2. J. Clarke, G. I. Hoffer, P. L. Richards, and N.-H. Yeh, Superconductive Bolometers for Submillimeter Wavelengths, J. Appl. Phys. 48, 4865 (1977). (D)

3. D. P. Woody and P. L. Richards, Spectrum of the Cosmic Background Radiation, Phys. Rev. Lett. 42, 925 (1979). (S)

4. P. L. Richards, Direct Measurements of the Spectrum of the Near-Millimeter Cosmic Background, Physica Scripta 21, 610 (1980). (S)

5. P. L. Richards and L. T. Greenberg, Infrared Detectors for Low-Background Astronomy: Incoherent and Coherent Devices from One Micrometer to One Millimeter, Infrared and Millimeter Waves, Vol. 6, Kenneth J. Button, ed., (Acad. Press 1982) pp. 149-207. (D)

6. P. L. Richards and D. P. Woody, The Spectrum of the Microwave Background in IAU Symposium No. 92, G. O. Abell and P. J. E. Peebles, Eds. (D. Reidel, Boston, 1979) pp. 283-291. (S)

7. D. P. Woody and P. L. Richards, Near-Millimeter Spectrum of the Microwave Background, Astrophys. J. 248, 18 (1981). (S)

8. T. Timusk and P. L. Richards, Near-Millimeter Wave Bandpass Filters, Applied Optics 20, 1355 (1981). (F)

9. D. Britt and P.L. Richards, An Adiabatic Demagnetization Refrigerator for Infrared Bolometers, Int. J. Infrared and mm-Waves 2, 1083 (1981). (D)

10. P. L. Richards, Spectrum of the Microwave Background Radiation, Philos. Trans. R. Soc. London A307, 77 (1982). (S)

11. J. L. Bonomo, J. B. Peterson, P. L. Richards, and T. Timusk, Calibration of a Photometer for Measurement of the Cosmic Microwave Background, Gamow Cosmology LXXXVI, 341 (1986). (O)

12. P. L. Richards, Spectrum of the Microwave Background Radiation, Proc. of the II Bi-National Colloquium of the Alexander von Humboldt Foundation, 65 (1983). (S)

13. A. E. Lange, E. Kreysa, S. E. McBride, P. L. Richards, and E. E. Haller, Improved Fabrication Techniques for Infrared Bolometers, Int. J. Infrared and Millimeter Waves 4, 689 (1983). (D)

14. P. L. Richards, Spectrum of the Microwave Background Radiation, Mitteilungen der Astronomischen Gesellschaft 60, 175 (1983). (S)

15. J. B. Peterson, P. L. Richards, J. L. Bonomo, and T. Timusk, New Measurements of the Spectrum of the Cosmic Microwave Background, CIRP3 Proceedings, 183 (1984). (S)

16. J. B. Peterson, P. L. Richards, J. L. Bonomo, and T. Timusk, New Measurements of the Spectrum of the Cosmic Microwave Background, in Inner Space/Outer Space, E. W. Kolb et al., eds., Univ. of Chicago Press, Chicago/London, 1986, pp. 119/125. (S)

17. A. E. Lange, D. Nolte, and P. L. Richards, A Dichroic Beamsplitter for the FIR, Ninth Int. Conf. on Infrared and Millimeter Waves, Conference Digest 191 (1984). (F)

18. S. Sato, T. Matsumoto, K. Sakai, A. E. Lange, and P. L. Richards, A New Type of Low Pass Filter Made of Glass Beads, Ninth Int. Conf. on Infrared and Millimeter Waves, Conference Digest 126 (1984). (F)

19. H. Murakami, S. Hayakawa, T. Matsumoto, H. Matsuo, S. Sato, A. E. Lange, and P. L. Richards, Far-Infrared and Submillimeter Antenna of Low Side Lobe, Ninth Int. Conf. on Infrared and Millimeter Waves, Conference Digest 125 (1984). (O)

20. T. Matsumoto, S. Hayakawa, H. Murakami, S. Sato, A. E. Lange, P. L. Richards, and K. Sakai, Instrumentation for the Observation of Far-Infrared and Submillimeter Background Radiation, Ninth Int. Conf. on Infrared and Millimeter Waves, Conference Digest 119 (1984). (O)

21. J. B. Peterson and P. L. Richards, A Cryogenic Blackbody for Millimeter Wavelengths, Int. J. Infrared and Millimeter Waves 5, 1507 (1984). (O)

22. D. D. Nolte, A. E. Lange, and P. L. Richards, Far-Infrared Dichroic Band-Pass Filters, Appl. Opt. 24, 1541 (1985). (F)

23. P. L. Richards, Infrared Detectors for Space Astronomy, Bull. Am. Phys. Soc. 30, 626 (1985). (D)

24. J. B. Peterson, P. L. Richards, and T. Timusk, The Spectrum of the Cosmic Background Radiation at Millimeter Wavelengths, Phys. Rev. Lett. 55, 332 (1985). (S)

25. A. E. Lange, S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, P. L. Richards, and S. Sato, A Rocket-Borne Submillimeter Radiometer, Appl. Opt. 26, 401 (1987). (O)

26. S. Sato, S. Hayakawa, A. E. Lange, T. Matsumoto, H. Matsuo, H. Murakami, and P. L. Richards, Horn Antenna with Low Sidelobe Response for Observations of Diffuse Celestial Radiation, Appl. Opt. 26, 410 (1987). (O)

27. P. L. Richards, Measuring the Temperature of the Universe, Bull. Am. Phys. Soc. 32, 33 (1987). (S)

28. P. L. Richards, Spectrum of the Microwave Background, Comets to Cosmology Proceedings, London 1987, Lecture Notes in Physics, vol. 297, edited by A. Lawrence, (Springer-Verlag Berlin Heidelberg 1988), pp. 289-296. (S)

29. T. Matsumoto, S. Hayakawa, H. Matsuo, H. Murakami, S. Sato, A. E. Lange, and P. L. Richards, The Submillimeter Spectrum of the Cosmic Background Radiation, Astrophys. J. 329, 567 (1988). (S)

30. S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, S. Sato, A. E. Lange, and P. L. Richards, Cosmological Implication of a New Measurement of the Submillimeter Background, Publ. Astron. Soc. Japan 39, 941 (1987). (S)

31. A. E. Lange, D. Alsop, S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, P. L. Richards, and S. Sato, A Rocket-Borne Measurement of Interstellar Dust Emission at High Galactic Latitude, Interstellar Dust: Contributed Papers, NASA Conf. Publ. 3036, 303 (1989). (S)

32. S. Sato, S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, K. Sakai, A. E. Lange, and P. L. Richards, Submillimeter-Wave Low-Pass Filters Made of Glass Beads, Appl. Optics 28, 4478 (1989). (F)

33. T. Matsumoto, S. Hayakawa, H. Matsuo, H. Murakami, S. Sato, A. E. Lange, and P. L. Richards, Cosmic Background Radiation in the Submillimeter Range, Proc. Yamada Conf. XX on Big Bang, Active Galactic Nuclei & Supernovae, pp. 213-225, Universal Academy Press, Inc., Tokyo, Japan (1989). (S)

34. G. M. Bernstein, M. L. Fischer, P. L. Richards, J. B. Peterson, and T. Timusk, Anisotropy of the Diffuse Background at Millimeter Wavelengths, Astrophys. J. Lett. 337: L1, (1989). (A)

35. G. M. Bernstein, M. L. Fischer, P. L. Richards, J. B. Peterson, and T. Timusk, New Measurements of the Spectrum and Anisotropy of the Millimeter Wave Background, in SUBMILLIMETRE ASTRONOMY, G.D. Watt and A. S. Webster, Editors, Kluwer Academic Publ., Dordrecht/Boston/London, 1990, p. 79. (S,A)

36. P. T. Timbie, G. M. Bernstein, P. L. Richards, T. N. Gautier, G. H. Rieke, M. W. Werner, Submillimeter Cosmology with the Multiband Imaging Photometer for SIRTF, in SUBMILLIMETRE ASTRONOMY, G.D. Watt and A. S. Webster, Editors, Kluwer Academic Publ., Dordrecht/Boston/London, 1990, p. 53. (D)

37. P. T. Timbie, G. M. Bernstein, and P. L. Richards, An Adiabatic Demagnetization Refrigerator for SIRTF, IEEE Trans. Nuclear Science 36, 898 (1989). (D)

38. G. M. Bernstein, P. T. Timbie, and P. L. Richards, A 100 mK Bolometer System for SIRTF, Proc. Third Infrared Detector Workshop NASA Technical Memorandum 102209, Oct. 1989, p. 35. (A)

39. G. M. Bernstein, M. L. Fischer, P. L. Richards, J. B. Peterson, and T. Timusk, New Measurements of the Anisotropy and Spectrum of the Millimeter Wave Background, Proc. Workshop Particle Astrophysics: Forefront Experimental Issues, Eric B. Norman Editor, World Scientific Publishers Co., Singapore (1989) p. 123. (A)

40. P. T. Timbie, G. M. Bernstein, and P. L. Richards, Development of an Adiabatic Demagnetization Refrigerator for SIRTF, Cryogenics 30, 271 (1990). (D)

41. G. M. Bernstein, M.L. Fischer, P.L. Richards, J.B. Peterson, and T. Timusk, A Measurement of the Spectrum of the Cosmic Background Radiation from 1 mm to 3 mm Wavelength, Astrophys. J. 362, 107 (1990). (S)

42. P. L. Richards, Observations of the CMB Spectrum, in The Cosmic Microwave Background 25 Years Later, eds. N. Mandolesi and N. Vittorio, Kluwer Acad. Publ. Co., Dordrecht, The Netherlands, 1990, pp. 141-152. (S)

43. A.E. Lange, P.L. Richards, S. Hayakawa, T. Matsumoto, H. Matsuo, H. Murakami, and S. Sato, The 100 to 300 μm Diffuse Background: Spectrum of the Infrared Cirrus and New Limits on the Extragalactic Background, Astrophys. J. (to be published). (S)

44. G. Bernstein, S. Labov, D. Landis, N. Madden, Ian Millett, E. Silver, and P. Richards, An Automated Temperature Regulation System for Adiabatic Demagnetization Refrigerators, Cryogenics (to be published). (D)

45. M.L. Fischer, D.C. Alsop, A.C. Clapp, D.A. Cottingham, A.E. Lange, P.L. Richards, G. Smoot, J.O. Gundersen, T.C. Koch, P.R. Meinhold, P.M. Lubin, E.S. Cheng, and E. Kreysa, A Millimeter-Wave Anisotropy Experiment (MAX) to Search for Anisotropy in the Cosmic Background Radiation on Medium Angular Scales, After the First Three Minutes Workshop Proc. (to be published). (A)

Theses

1. Norman S. Nishioka, Composite Semiconductor Bolometers for the Detection of Far-Infrared Radiation, M.S. Thesis, December 1976.

2. J.L. Bonomo, Two Instruments for Far Infrared Astrophysics, Ph.D. Thesis, May 1983.

3. J.B. Peterson, The Spectrum of the Cosmic Background Radiation from 2.3 cm^{-1} to 11.0 cm^{-1}, Ph.D. Thesis, April 1985.

4. A.E. Lange, An Attempt to Measure the Diffuse Brightness of the Sky at Submillimeter Wavelengths, Ph.D. Thesis, January 1987.

5. F. Rieke, DC Coupled Bolometers for Infrared Astronomy, Undergraduate thesis, June 1988.

6. G.M. Bernstein, Measurements of the Spectrum and Anisotropy of the Millimeter Wave Background, Ph.D. Thesis, September 1989.